Advanced Radioisotope Power Systems Technology development at JPL

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presented by

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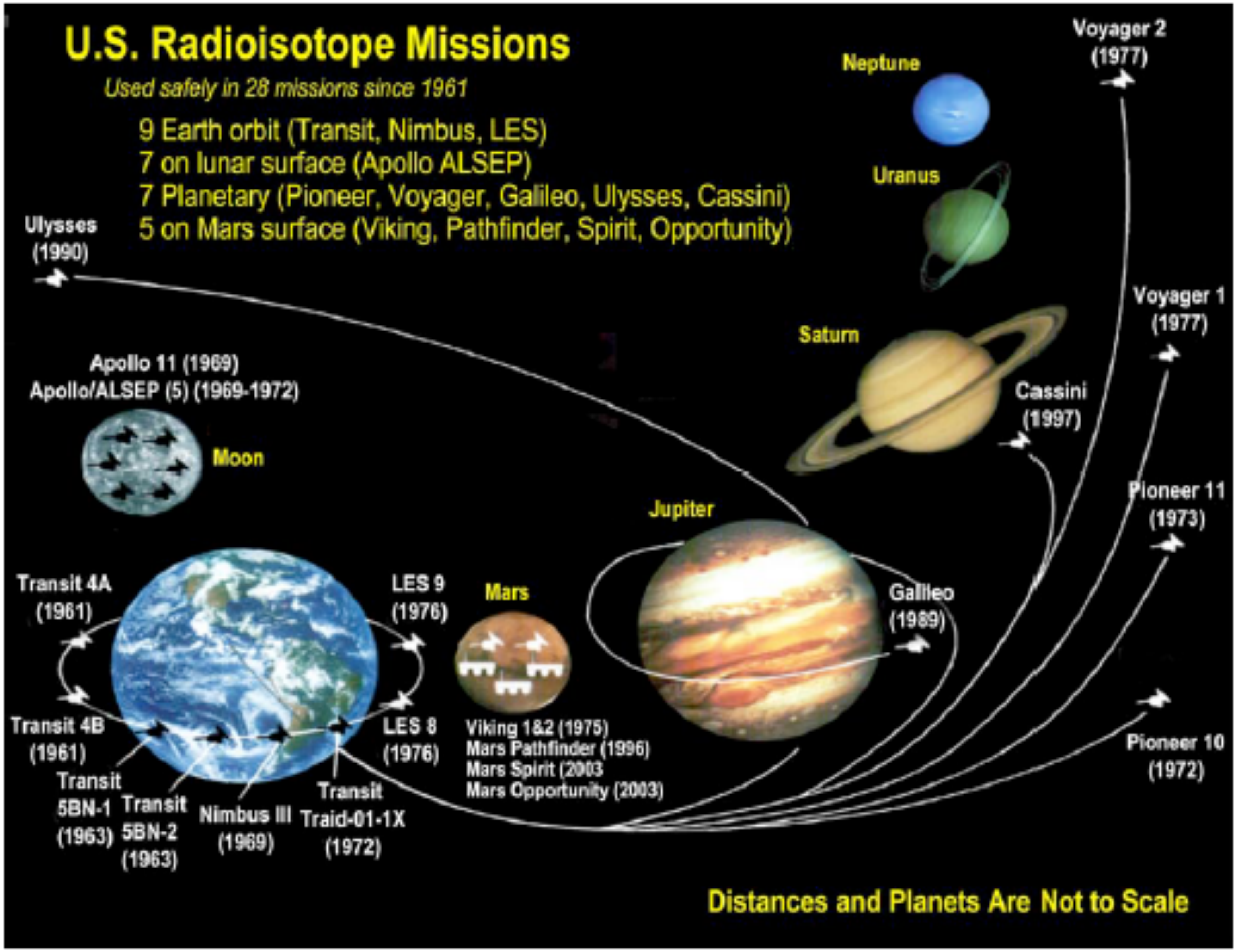
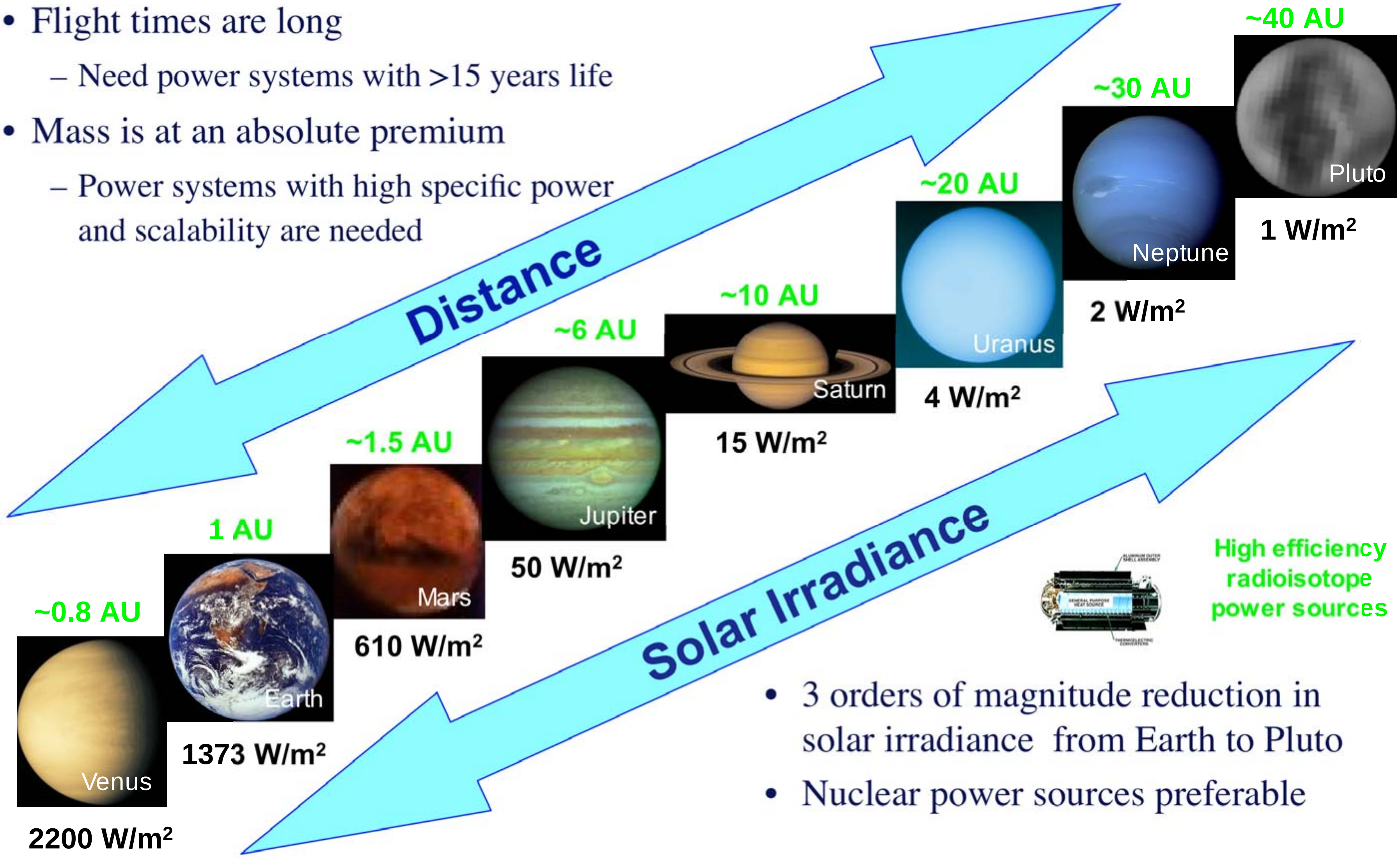
Jet Propulsion Laboratory/California Institute of Technology

U.S. missions using radioisotopes power and/or heating sources



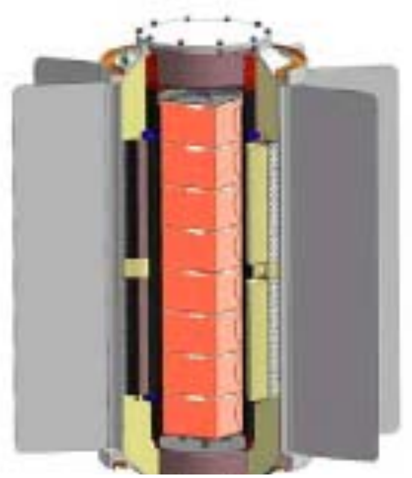
Power Technology

- Flight times are long
  - Need power systems with >15 years life
- Mass is at an absolute premium
  - Power systems with high specific power and scalability are needed

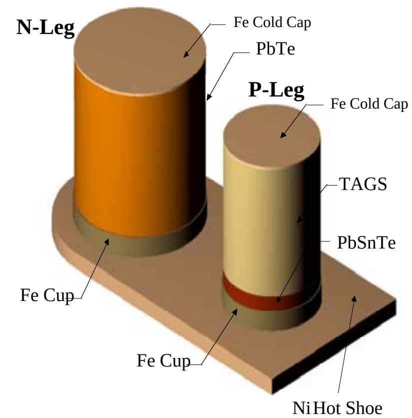


- 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Nuclear power sources preferable

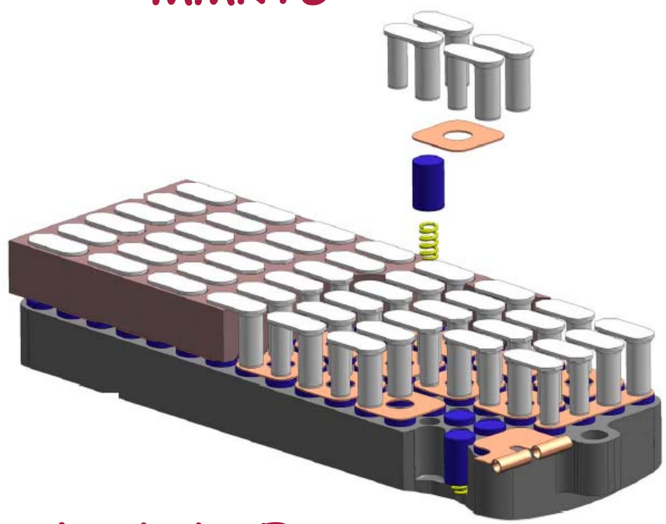
Multi-Mission PbTe/TAGS conductively coupled RTG (MMRTG)



MMRTG



MMRTG couple



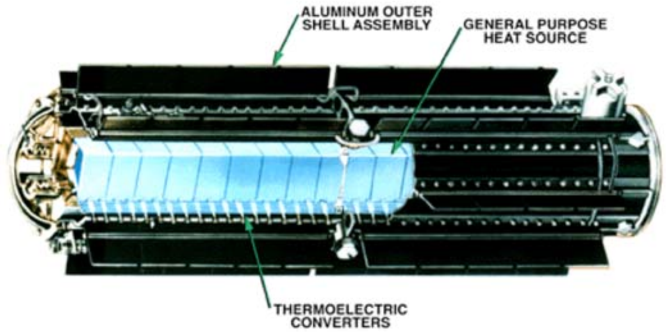
Spring-loaded TE converter

Item/Converter	PbTe/TAGS MMRTG
Hot side temperature (K)	**823**
Cold side temperature (K)	**483**
Converter efficiency (%)	**7.6**
System efficiency (%)*	**6.4**
Thermal power (BOM)(W_{th})	2000
Thermal efficiency (%)	
Electrical power (BOM) (W_e)	125.3
Number of GPHS modules	8
Total PuO_2 mass (kg)	**5.02**
Total system mass estimate (kg)	**43.8**
Specific power estimate (W_e/kg)	**2.85**

General Purpose Heat Source RTG

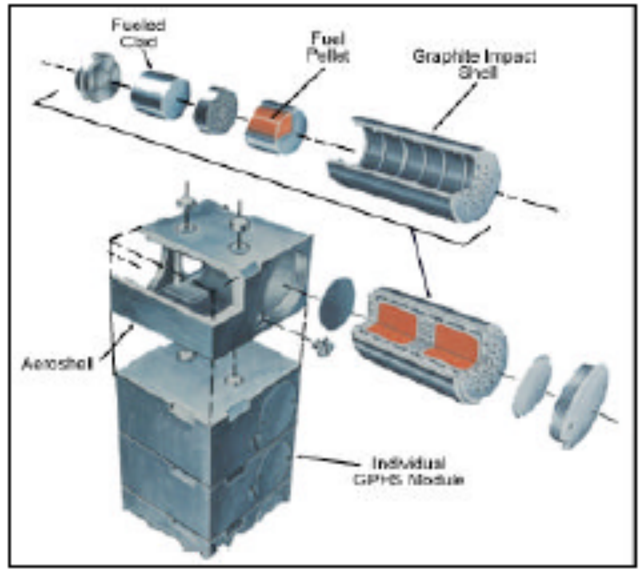
General Purpose Heat Source (GPHS)

Radioisotope Thermoelectric Generator (RTG)

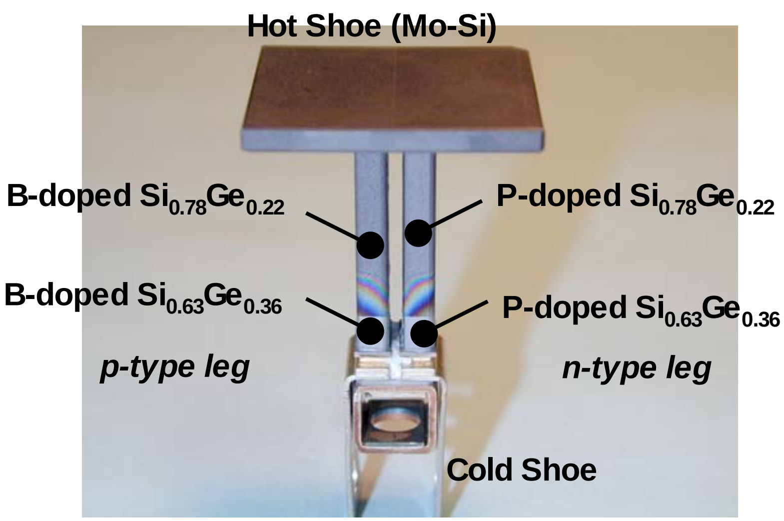


- POWER OUTPUT – 285 W(e)
- FUEL LOADING – 4400 W(t); 132,500 Ci
- WEIGHT – 124 lbs
- SIZE – 16.6 in x 44.5 in

The three Radioisotope Thermoelectric Generators (RTGs) provide electrical power for Cassini's instruments and computers. They are being provided by the U.S. Department of Energy.



General Purpose Heat Source Module



GPHS SiGe unicouple

GPHS-RTG Performance Data

Power output-We	290 beginning of life 250 end of life
Operational life - hrs	40,000 after launch
Weight-kg	55.5
Output voltage	28
Dimensions	42.2 diameter 114 long
Hot junction temperature-K	1270
Cold junction temperature-K	566
Fuel	PuO_2
Thermoelectric material	SiGe
Numbers of unicouples	572
Mass of Pu-238-g	7,561

Advanced Radioisotope Power Systems (APRS) for NASA missions

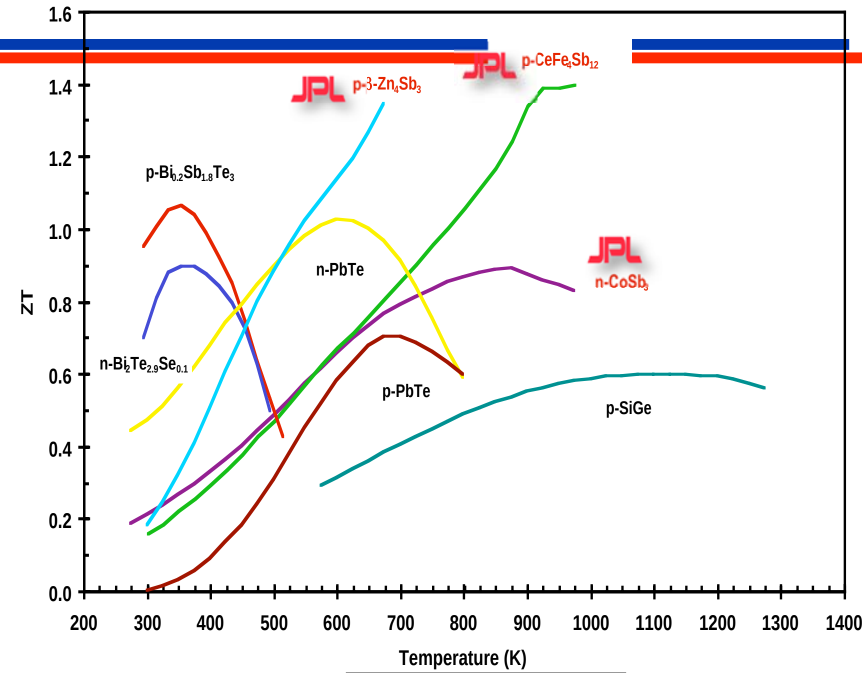
- **Overall objective:**

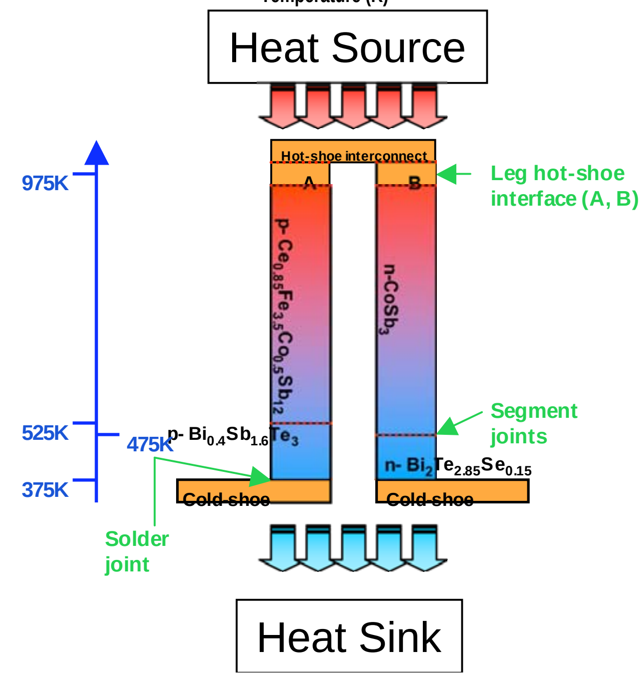
  Develop low mass, high efficiency, low-cost Advanced Radioisotope Power System with double the Specific Power and Efficiency over state-of-the-art Radioisotope Thermoelectric Generators (RTGs)

Segmented Thermoelectric Technology (STE)

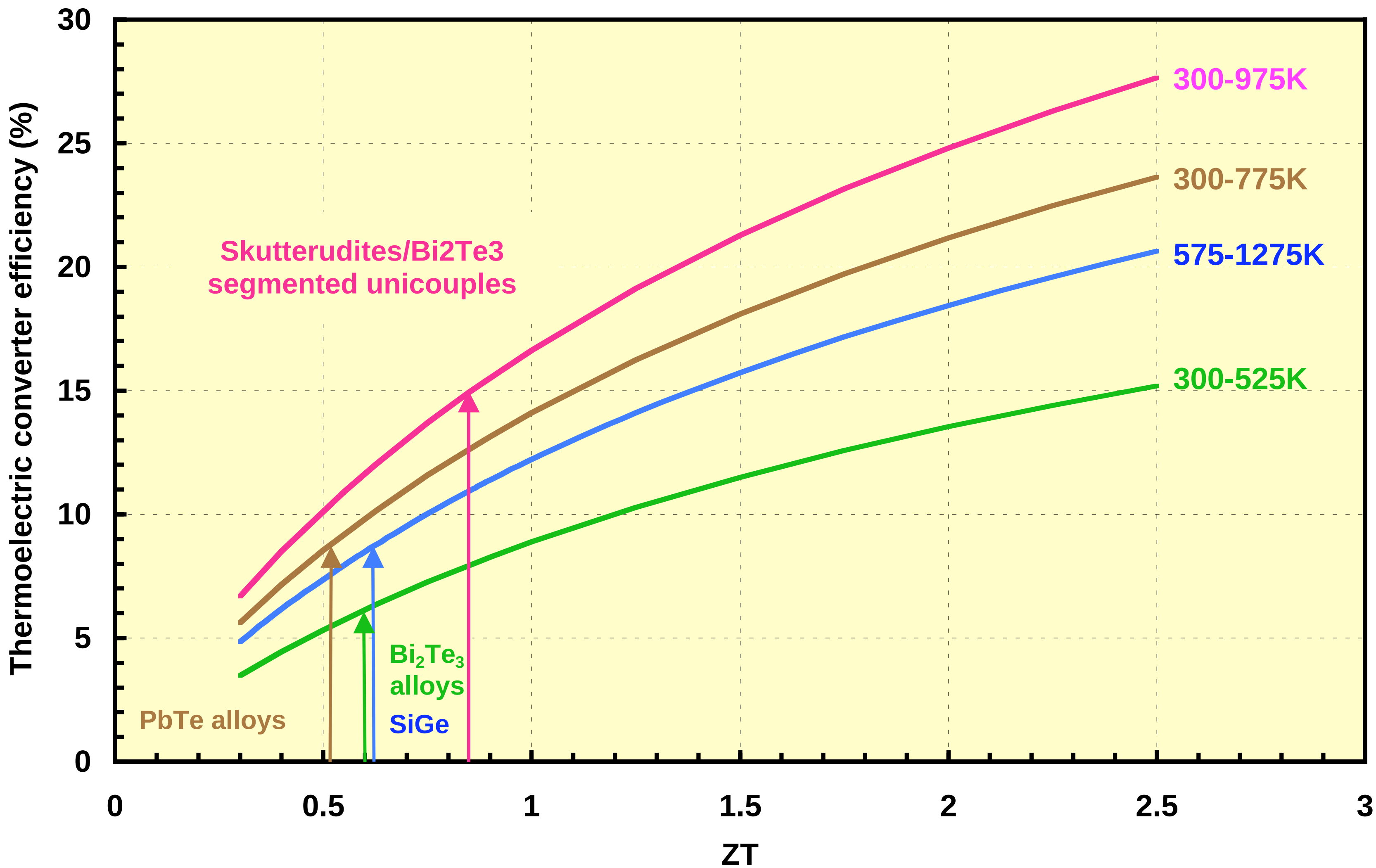
- **New high ZT materials**
  - **Development initiated in 1991 and supported by ONR and DARPA**
  - **Higher efficiency values**
- **Segmented unicouples**
  - **Large ΔT, high ZT -> high efficiency**
  - **Using a combination of state-of-the-art TE materials (Bi_2Te_3-based materials) and new, high ZT materials developed at JPL**
    - **Skutterudites : $CeFe_4Sb_{12}$ and $CoSb_3$**
    - **Zn_4Sb_3**
  - **Current materials operation limited to ~ 975K**
  - **Higher average ZT values**
  - **Higher material conversion efficiency**
    - **Up to 15 % for a 300-975K temperature gradient**

Efficiency $$\eta = \frac{T_H - T_C}{T_H} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}$$



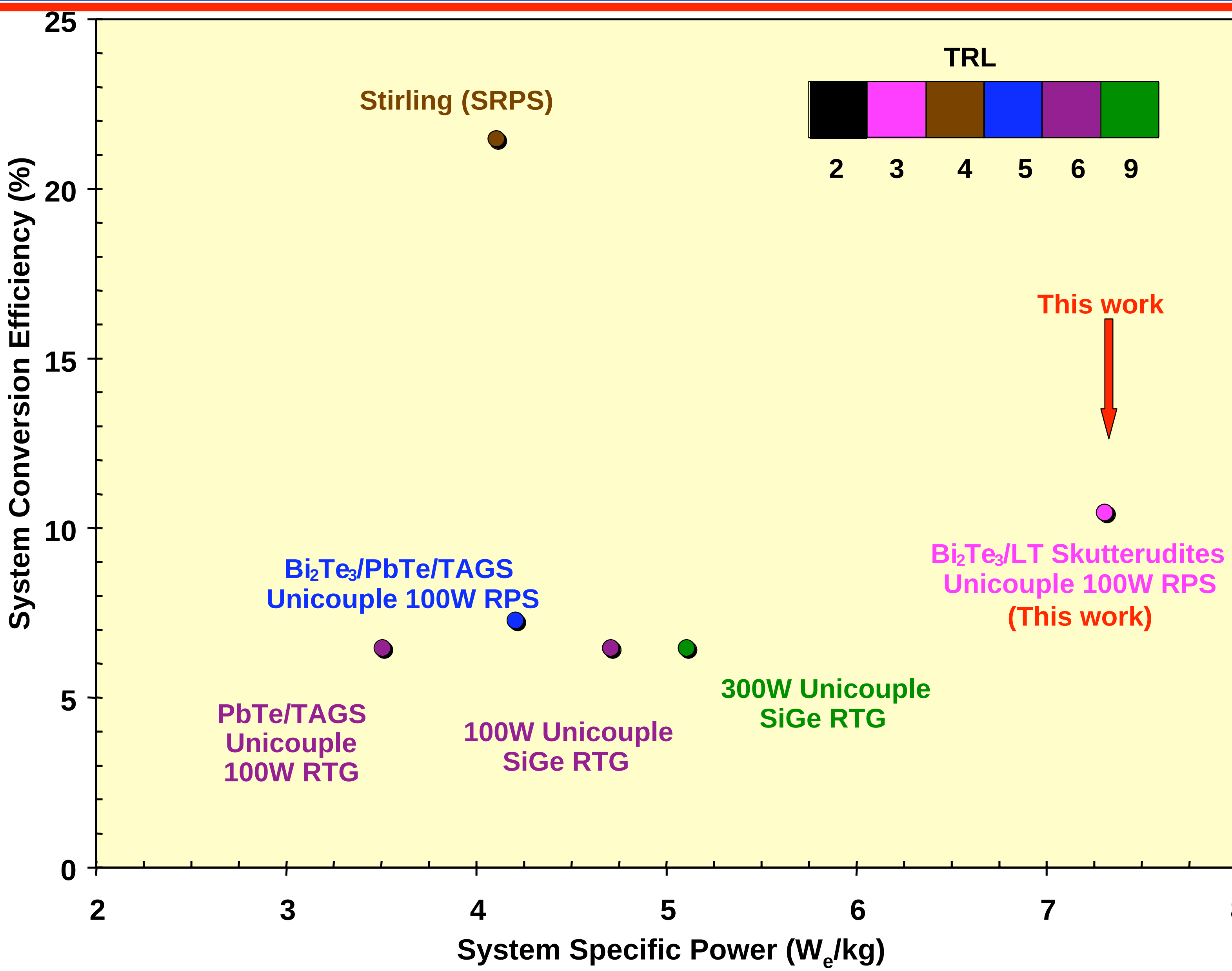


Converter efficiency : state-of-the-art vs. segmented thermoelectric technology



STE technology has the potential for achieving twice the converter efficiency of SOA thermoelectrics

System Efficiency & Specific Power: STE vs. SOA



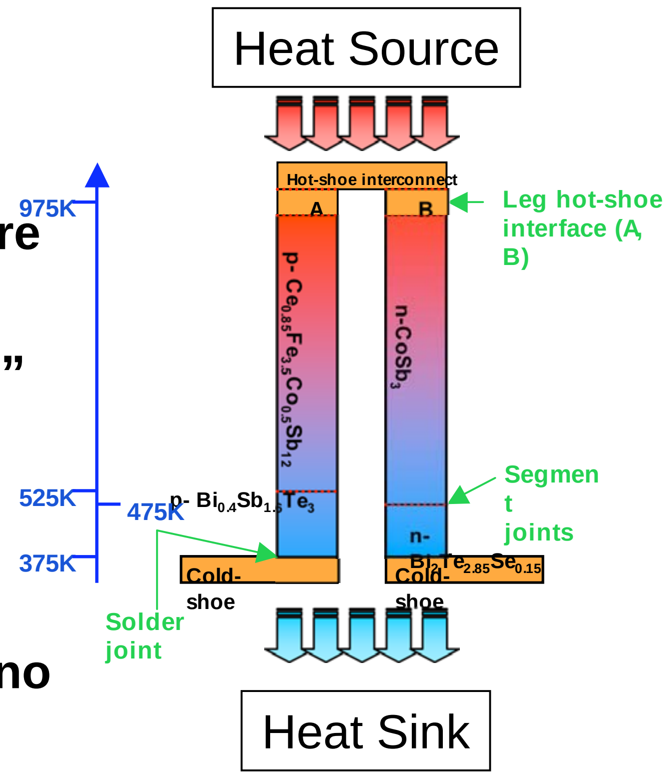
STE-ARPS

- Would use advanced materials segmented legs
- 700 to 100^{o}C operation
- Current GPHS-RTG unicouple design would be mostly conserved
- Modifications required to radiator fins to accommodate for lower rejection temperature
- Shorter housing

➢ New segmented unicouples could “replace” unicouples almost “one for one”

Advantages of thermoelectrics

- Flight proven, long life demonstrated
- Solid state energy conversion -> reliability, no vibration, no moving parts
- Scalable
- No single point failure
- Significant system heritage

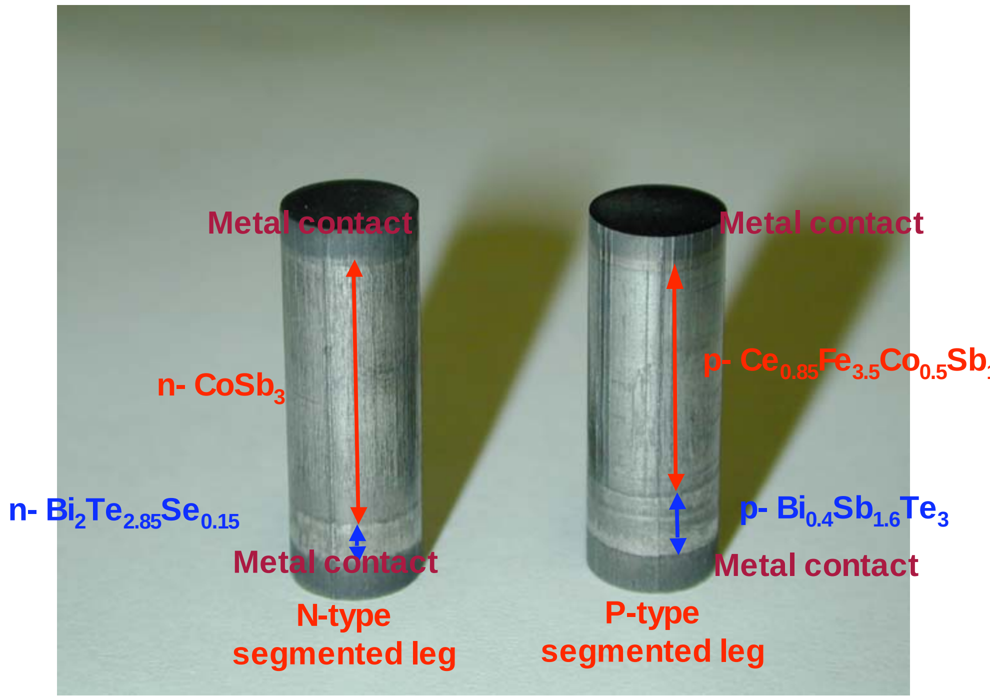


Synthesis and properties for n-$CoSb_3$ and $Ce_1Fe_3Ru_1Sb_{12}$

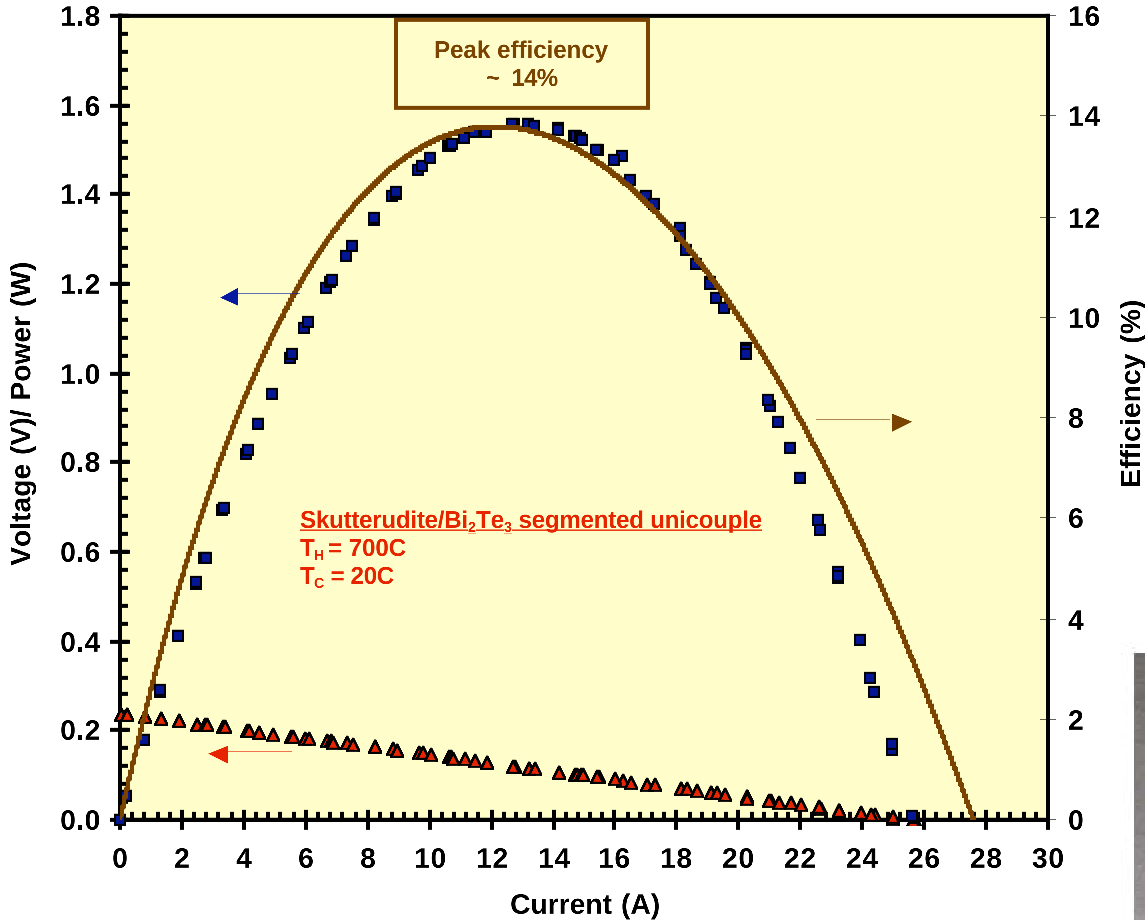
- **Synthesis**
  - Melting (~1200C in BN crucibles) and milling in steel vials under Argon
  - Hot pressing at temperatures between 600 and 700C, graphite dies, 20,000 psi
  - Developed 100g batch process for n-type and p-type
  - Overall process similar to SOA thermoelectrics; powder metallurgy process easily scalable to larger quantities
- **Properties**
  - N-type $CoSb_3$
    - Uses Pd, Te (~ 1at% each) as dopants to optimize carrier concentration
    - CTE: 9.1 x 10^{-6}K
    - Decomposition temperature: 878C
  - $Ce_{0.85}Fe_{3.5}Co_{0.5}Sb_{12}$
    - CTE: 12.1 x 10^{-6}K
    - Decomposition temperature: 778C
  - Mechanical property measurements in progress

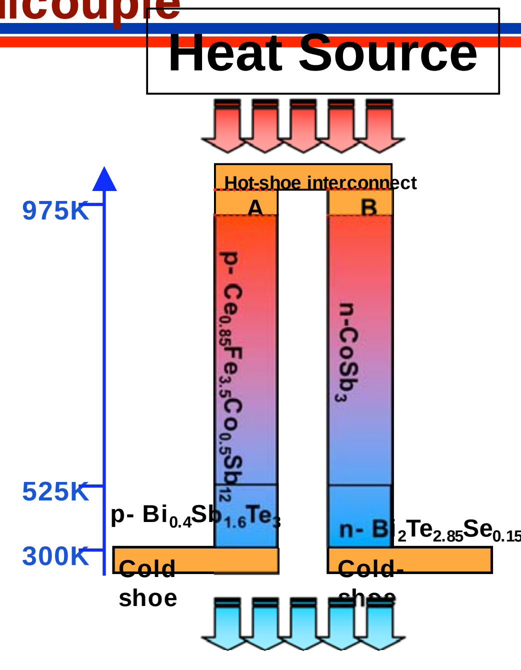
Unicouples legs

- **Developed uniaxial hot-pressing technique for legs fabrication**
  - **Powdered materials stacked on the top of each other**
  - **Temperature optimized → density close to theoretical value**
  - **In graphite dies and under argon atmosphere**
  - **With metallic diffusion barriers between the thermoelectric materials**
  - **Metallic contacts at hot- and cold-side**
  - **Low electrical resistance bonds (<5μ Ωcm²) achieved ➔ negligible impact on overall unicouple performance**



Thermal and electrical testing - Segmented unicouple





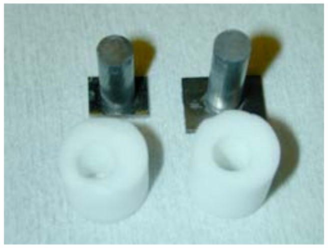

Skutterudite unicouples fabricated by diffusion bonding

- **Experimental I-V curves fully validate projected performance**
  - **Translate into ~ 14% efficiency for 975K-300K ΔT**
- **Results independently confirmed at the University of New Mexico**

Sublimation Suppression November 2004

- Completed in-gradient experiment on an n-an p-type leg pressed at 535C and bonded to a Mo plate
  - A single p-leg (6 mm long) was bonded to a Mo plates
  - Tested in 700C-100C gradient for 7 days with a 4mm thick, machined, titania opacified/150 mg/cc aerogel donut
  - Post cross-sectional analysis showed that: both the leg and the aerogel indicated that there were no signs of significant sublimation (no noticeable depletion bands in the leg and no condensation inside the aerogel or on the inner wall of the ampoule

Single skutterudite leg bonded to a Mo hot-shoe



Bonded legs with machined aerogel donuts

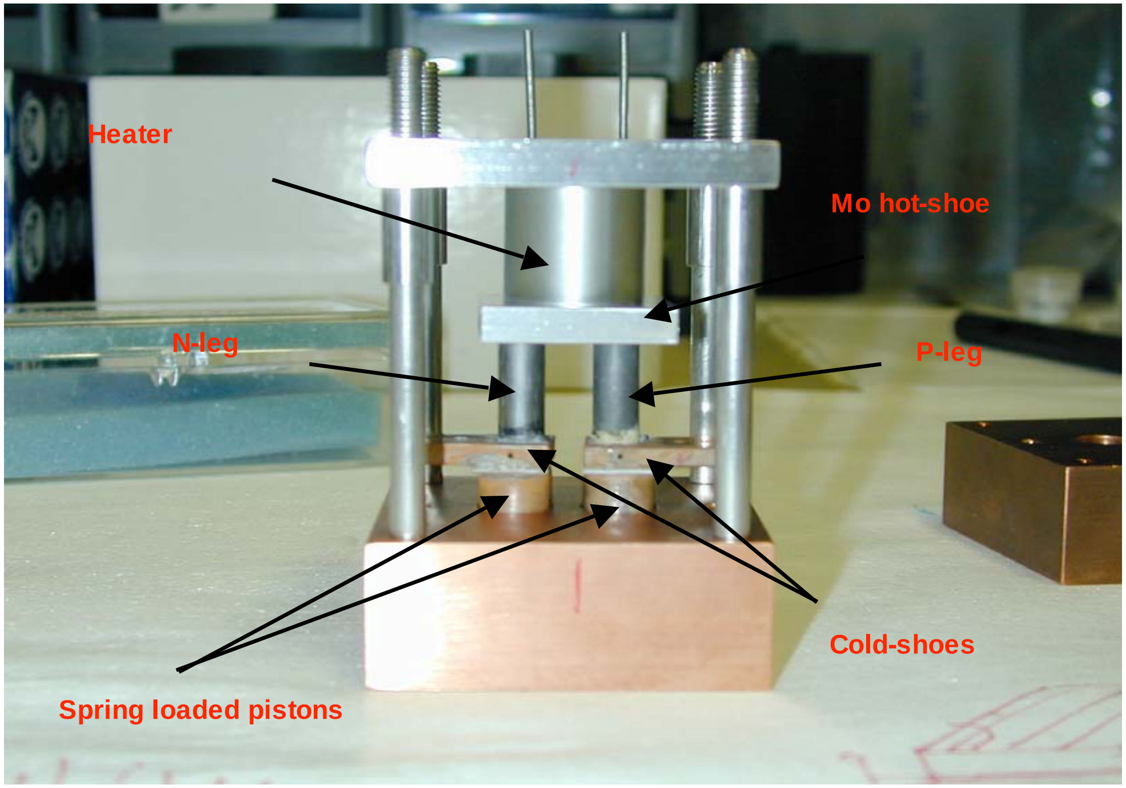
In-gradient test set-up

SEM picture of cross section near the Mo/leg interface after 7 days at 700C: no sublimation was observed

Photograph of aerogel donut cut in half after 7 days at 700C in contact with skutterudite leg: no sublimation deposit was observed

Spring loaded unicouple test fixture development

- Fabricated 1st generation spring loaded test fixtures



P- and n-skutterudite legs mounted in spring loaded test fixture

Lifetime performance demonstration elements

THERMOELECTRIC PROPERTIES (FY04)

Examples :
- SiGe: dopant precipitation
- Fine grained SiGe: grain growth
- TAGS : compositional change

Testing:
- Coupons

Impact:
- Change in efficiency, P output

Solution:
- Composition, doping control

MATERIALS SUBLIMATION (FY04)

Examples :
- SiGe: Si & Ge
- TAGS, PbTe: Te, Se, Ag, Sb
- Skutterudites : Sb

Testing:
- Coupons

Impact:
- A/l, porosity, contact resistance, mechanical failure

Solution:
- Encapsulation, coatings
- More refractory materials

THERMAL INSULATION (FY05-06)

Examples :
- Si in MFI

Testing:
- Unicouple

Impact:
- Shorting
- Contamination

Solution:
- Processing and engineering control

THERMO-MECHANICAL INTEGRITY (FY05-06)

Testing:
- Unicouple

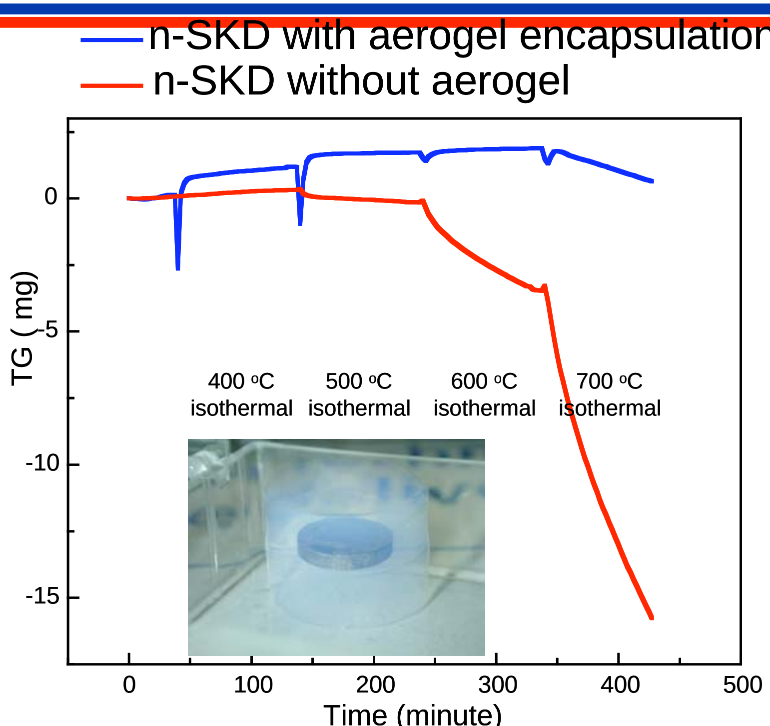
Impact:
- Contact resistance
- Mechanical failure

Solution:
- Device engineering/modeling

LIFETIME MODEL

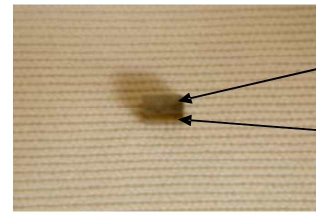
FUEL DECAY

Sublimation Suppression with Aerogel Encapsulation



Sample	Temperature	Sublimation rate in vacuum (~ 2 ×10^{-6} Torr)
n-SKD without aerogel	500 °C	5.31 × 10^{-4} g/cm^2 hr
	600 °C	5.16 × 10^{-3} g/cm^2 hr
	700 °C	2.15 × 10^{-2} g/cm^2 hr
n-SKD with aerogel encapsulation	500 °C	-
	600 °C	-
	700 °C	2.70 × 10^{-3} g/cm^2 hr

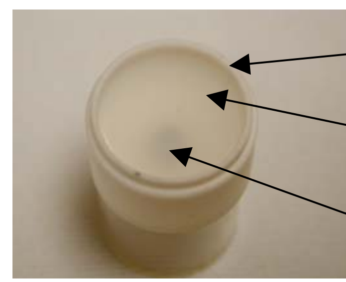
n-SKD cube (3 mm×3 mm×1.7mm) for the sublimation test



n-type SKD

Ti

n-SKD cube encapsulated with aerogel (before sublimation test)

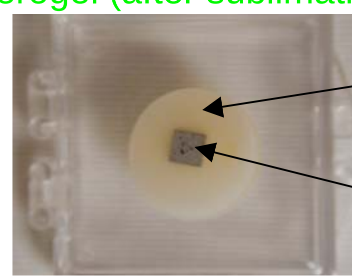


Alumina crucible for TGA

Silica aerogel with alumina powder

n-type SKD

Bottom view of n-SKD cube encapsulated with aerogel (after sublimation test)



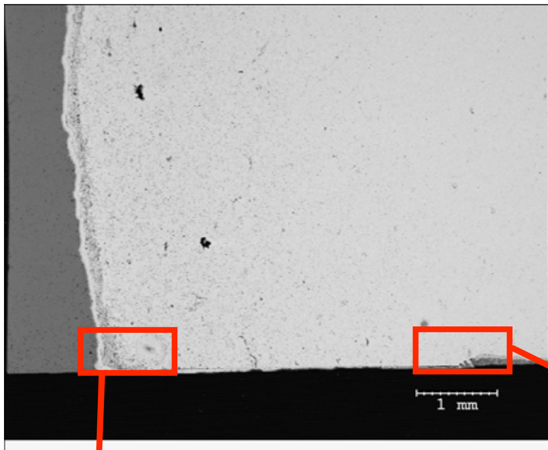
Silica aerogel with alumina powder

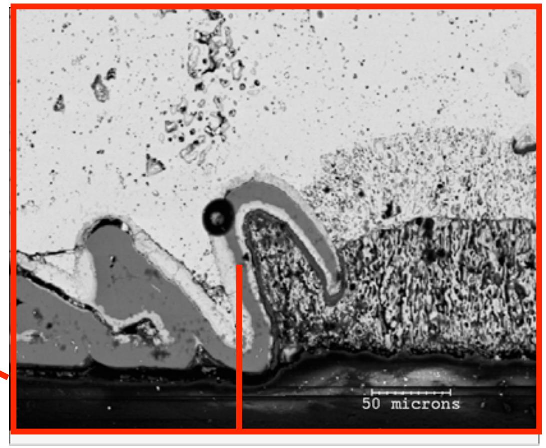
Ti at the bottom of n-type SKD

Sublimation Suppression with Thin-film Coating

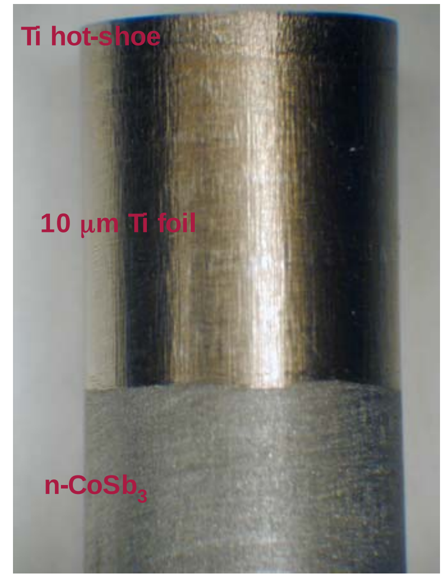
Ti coated n-type tested in-gradient for 20 days

975K ⟶

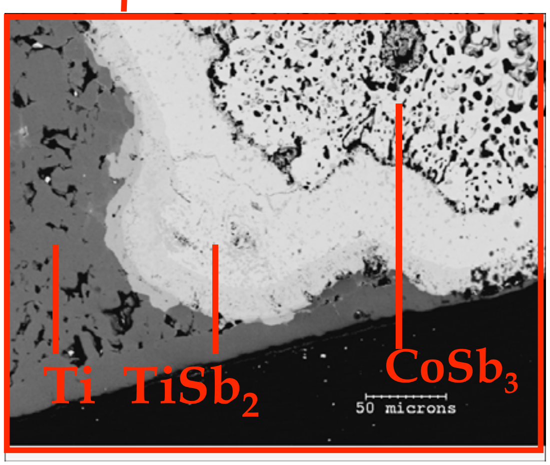




Coating stops



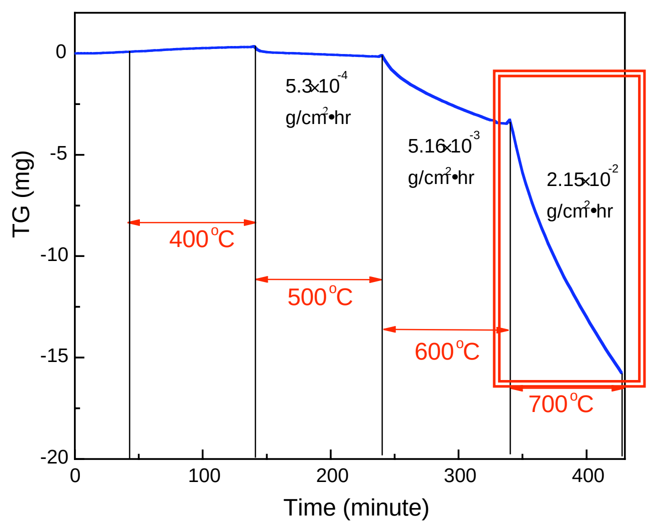
N-type Ti coated skutterudite leg



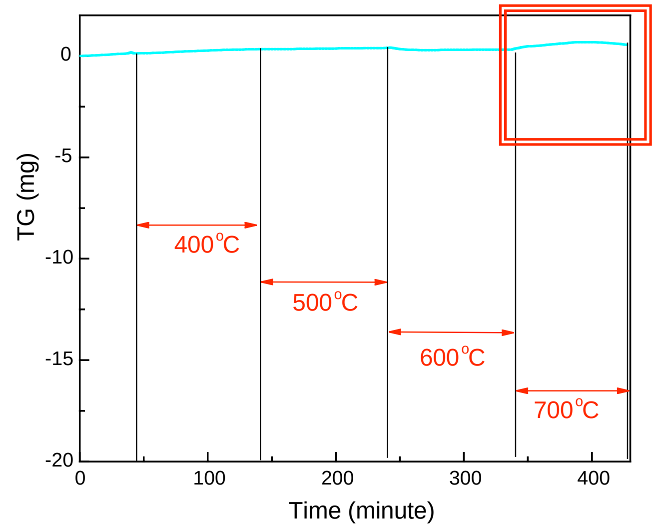
- No apparent degradation after 20 days
- Metal junction still intact
- Significant improvement over uncoated

Aerogel and Ti/Mo Coatings Significantly Reduce Sublimation at BOL

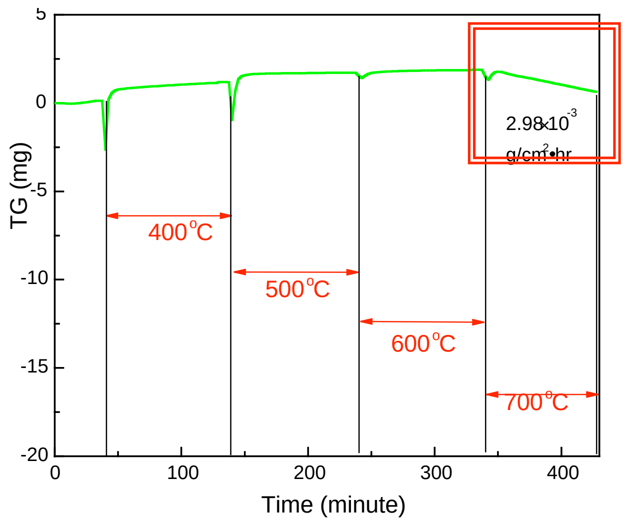
Uncoated



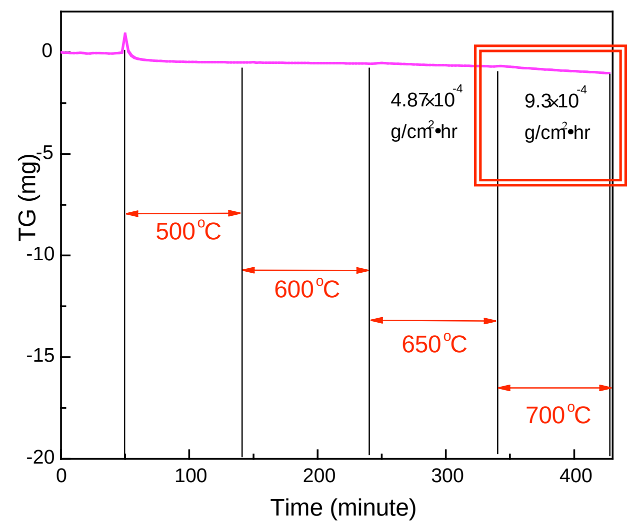
Titanium/Molybdenum Foil



Low Density Aerogel (50 mg/cm³)



Higher Density Aerogel (100 mg/cm³)



Skutterudite materials temperature stability/performance optimization: $Ce_1Fe_{4-x}Ru_xSb_{12}$ system

	Composition	Decomposition temperature
DGF277	$Ce_1Fe_4Sb_{12}$	760.6 °C
NSKP5	$Ce_1Fe_3Ru_1Sb_{12}$	830.7 °C
NSKP6	$Ce_1Fe_2Ru_2Sb_{12}$	850.6 °C
NSKP10	$Ce_1Fe_1Ru_3Sb_{12}$	955.8 °C
NSKP11	$Ce_1Ru_4Sb_{12}$	994.3 °C

➥ Results indicate increasing decomposition temperature trend with increasing Ru concentration

Sublimation rates from TGA measurement in dynamic vacuum

High temperature skutterudite sublimation rates at beginning of test

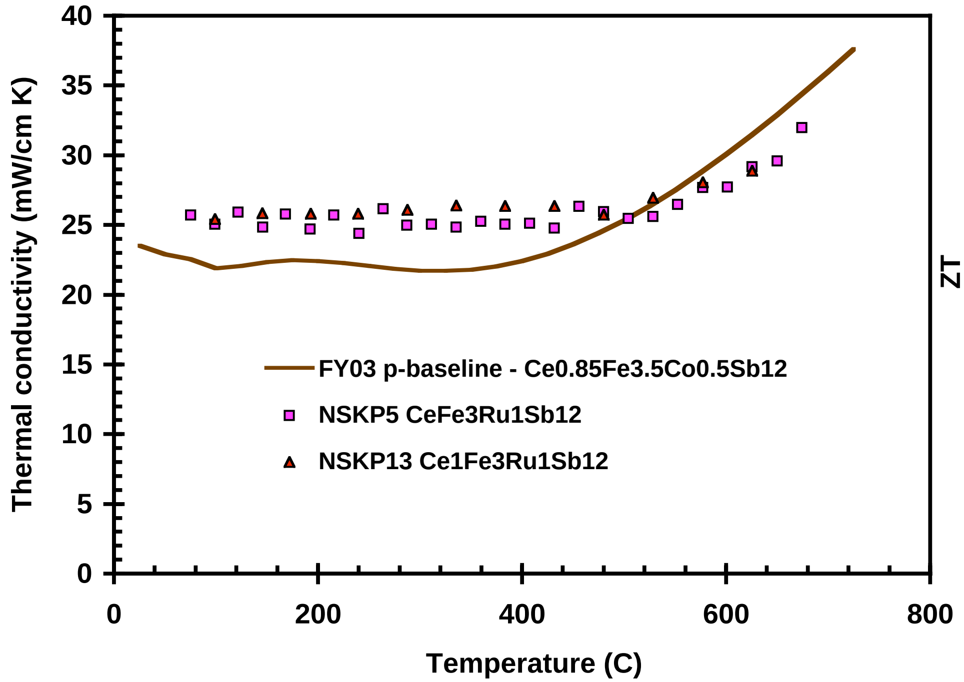
	Sublimation rate of n-SKD ($IrSb_3$)	Sublimation rate of p-SKD ($CeRu_4Sb_{12}$)
600 °C	3.88×10^{-5} (g/cm²·hr)	1.32×10^{-4} (g/cm²·hr)
700 °C	9.61×10^{-4} (g/cm²·hr)	7.91×10^{-4} (g/cm²·hr)
800 °C	3.92×10^{-3} (g/cm²·hr)	1.65×10^{-3} (g/cm²·hr)
900 °C	1.66×10^{-2} (g/cm²·hr)	1.05×10^{-2} (g/cm²·hr)

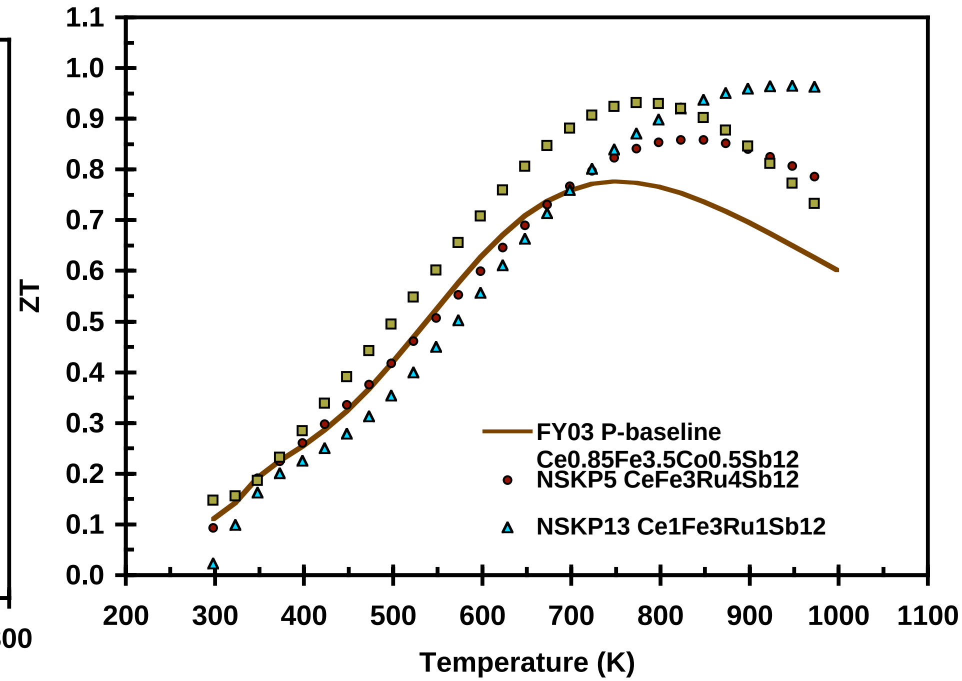
Skutterudite sublimation rates at beginning of test

	Sublimation rate of n-SKD	Sublimation rate of baseline p-SKD ($Ce_{0.85}Fe_{3.5}Co_{0.5}Sb_{12}$)	Sublimation rate of new p-SKD ($Ce_1Fe_3Ru_1Sb_{12}$)
500 °C	5.31×10^{-4} (g/cm²·hr)	7.40×10^{-4} (g/cm²·hr)	1.70×10^{-4} (g/cm²·hr)
600 °C	5.16×10^{-3} (g/cm²·hr)	6.78×10^{-3} (g/cm²·hr)	4.12×10^{-4} (g/cm²·hr)
700 °C	2.15×10^{-2} (g/cm²·hr)	2.80×10^{-2} (g/cm²·hr)	1.40×10^{-3} (g/cm²·hr)

Decreasing sublimation rates

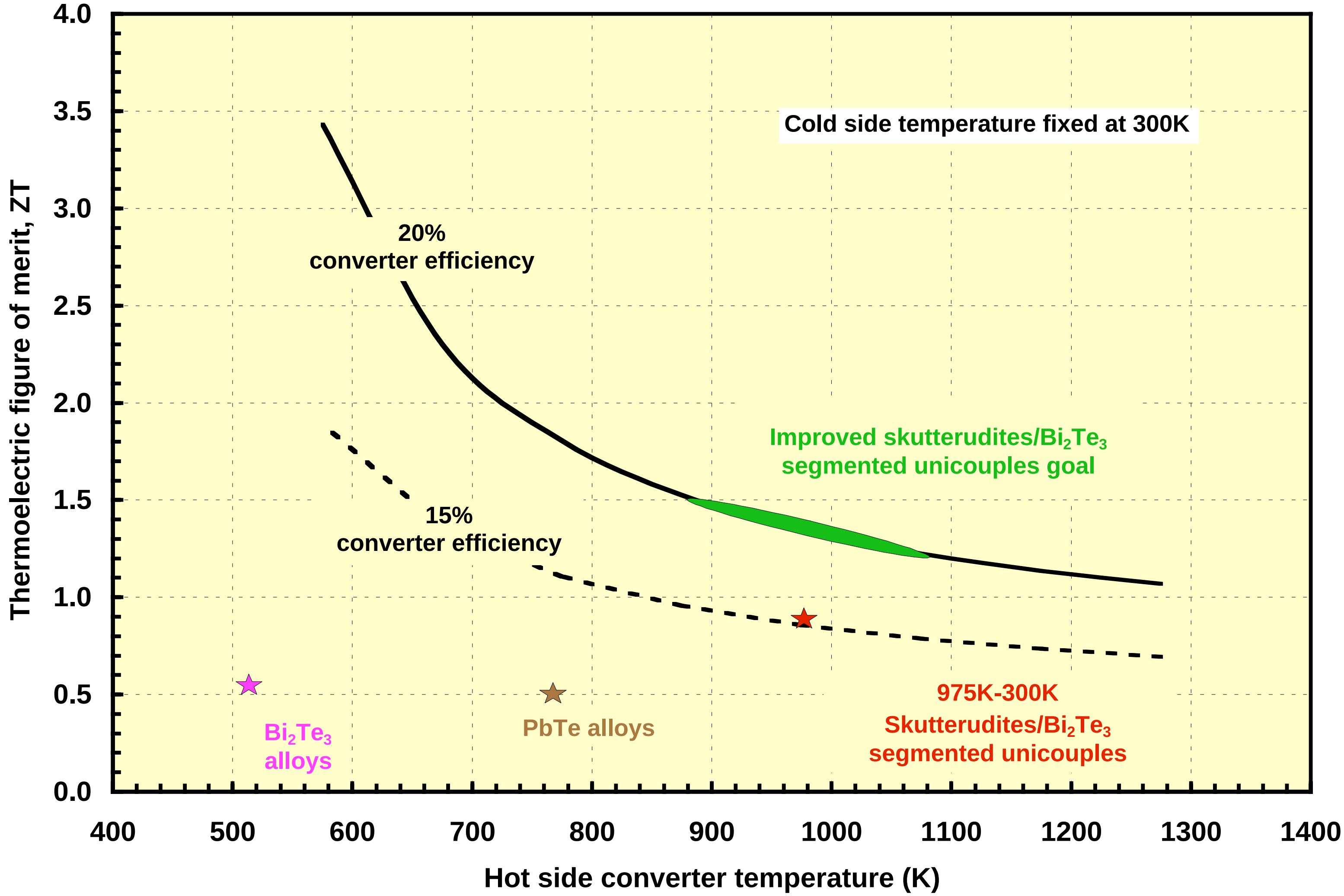
Thermal conductivity and ZT versus temperature for p-type materials





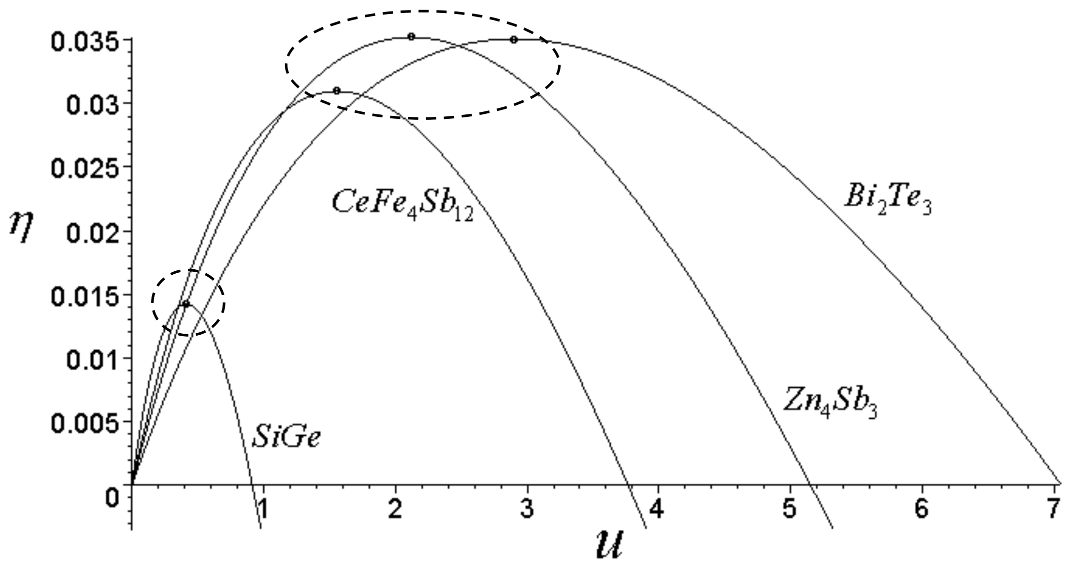
- Developed second generation p-type $CeFe_3Ru_1Sb_{12}$TE material that possesses improved ZT and higher temperature stability (1100K) than $Ce_{0.85}Fe_{3.5}Co_{0.5}Sb_{12}$ baseline material

Achieving 20% Converter efficiency

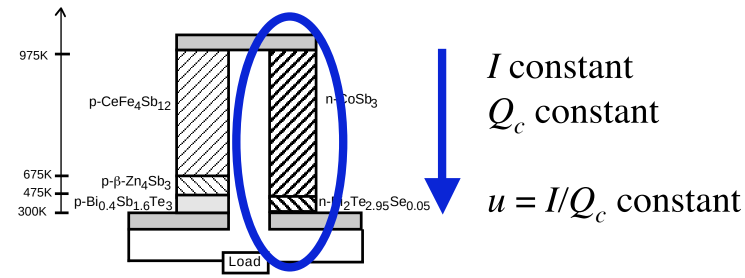


TE Device Configuration: Segmenting *vs* Cascading

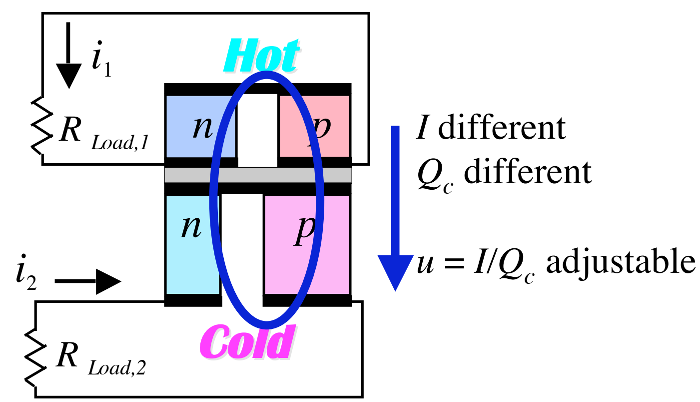
- Segmented Thermoelectric
  - **constrained by constant current**
    - ***u = I/Q$_c$***
    - ***u ≈ Constant***
- Cascaded Thermoelectric
  - **independent circuits for each stage**
    - **Current different in each stage**
    - **Heat different in each leg**
    - ***u* optimized for each stage**

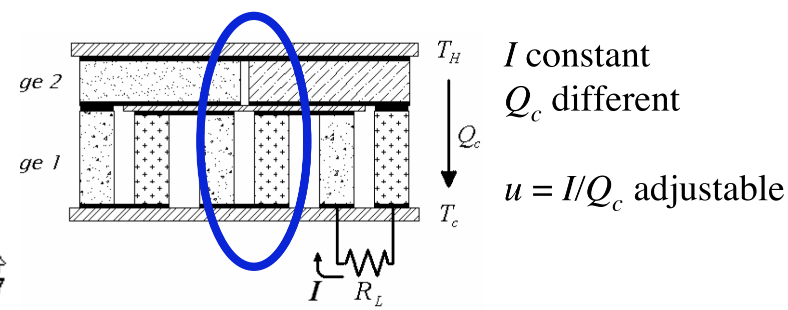


Segmented TE Generator

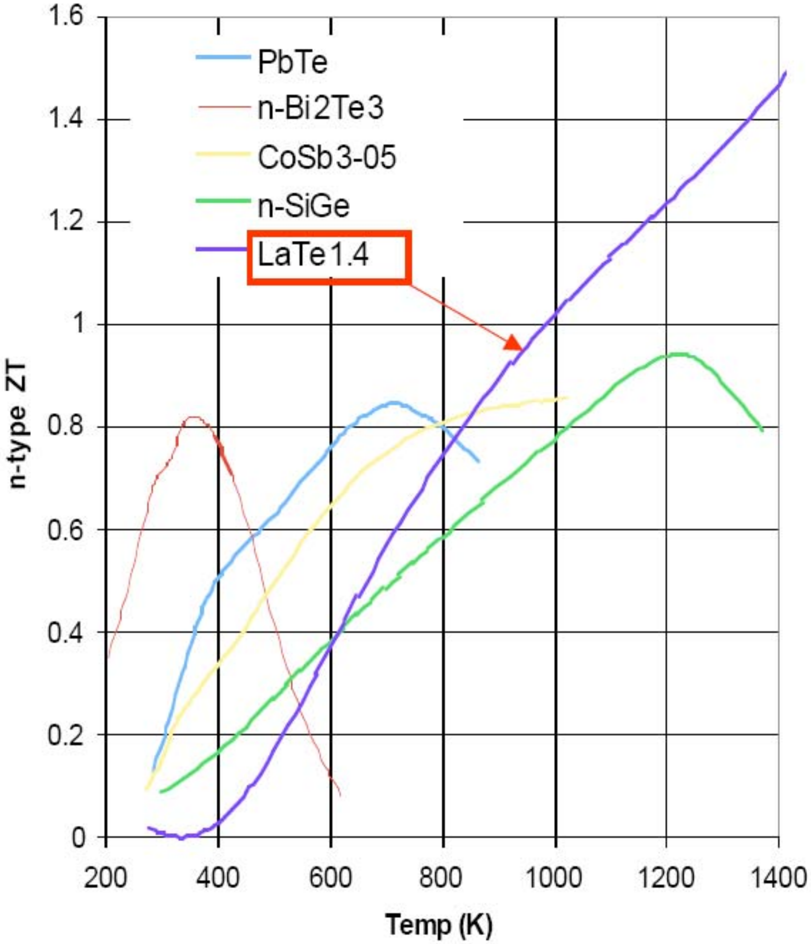


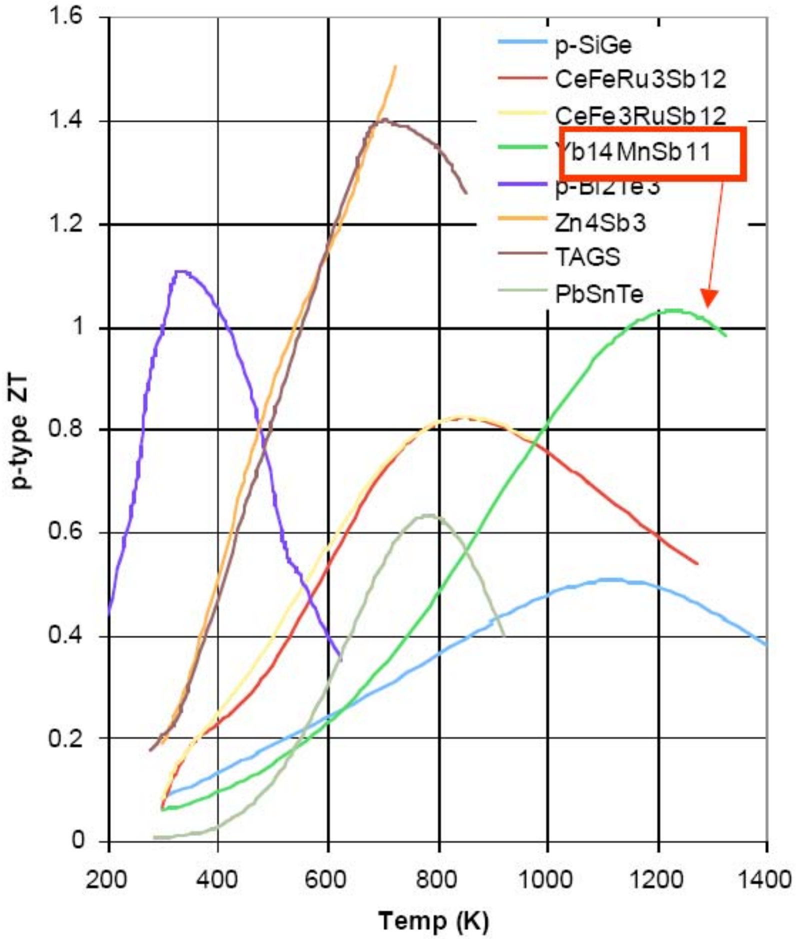
Cascaded TE Generators





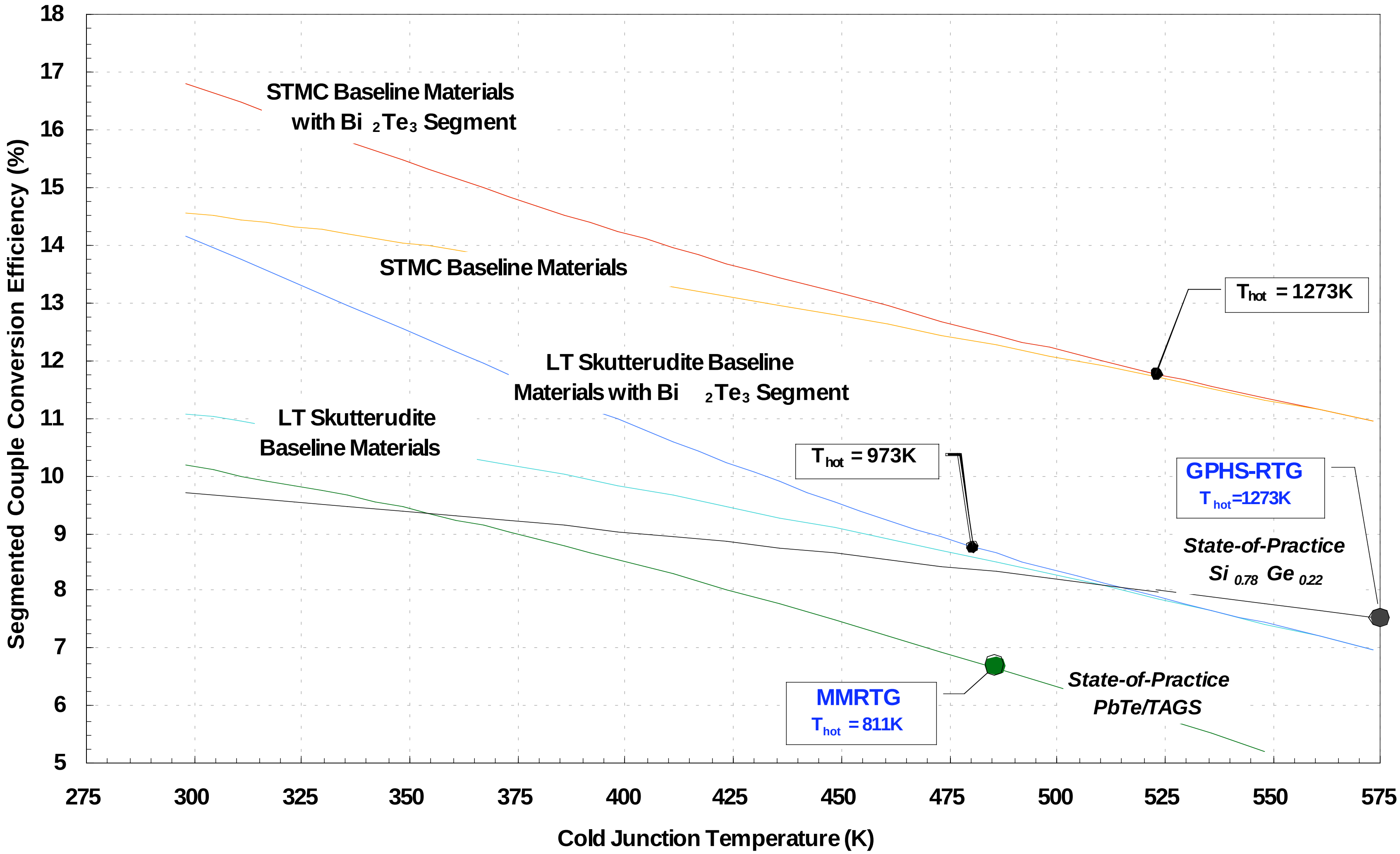
Best TE Materials to Date





High-T materials are currently developed under STMC Task

Advanced Materials Thermoelectric Conversion Efficiency

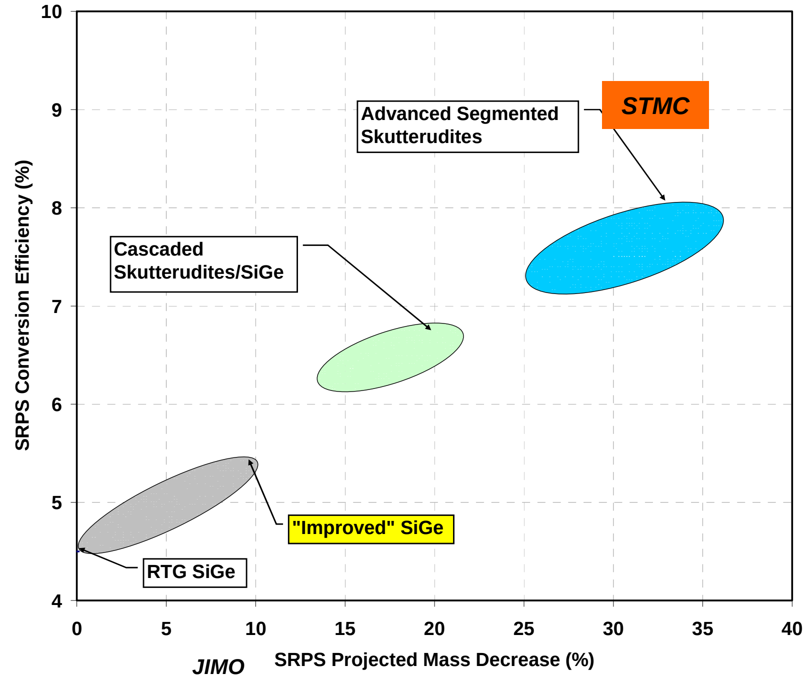


Potential High Power Thermoelectric Converter Technology Development for Future High Power Science Missions

- **Segmented Thermoelectric Multicouple Converter (STMC) technology for 100 kWe class power systems**

- **Primary objective is technology development based on high performance advanced thermoelectric materials for potential future NASA missions**
  - 2x increase in conversion efficiency
  - High rejection temperature (600-700K)
    - Limit size of heat rejection system
    - And minimize overall system mass

- **Scope focused on:**
  - Power Conversion System design and modeling
  - Advanced TE materials evaluation and optimization
  - Advanced TE Couple Array engineering development
  - Scale-up converter fabrication
  - Planning for technology insertion



100kW Thermoelectric Space Power System Goals

Projected Performance Improvements using Advanced TE Materials over SiGe Alloys used in RTGs

STMC TE Technology Development Team

- Jet Propulsion Laboratory
- Boeing/Rocketdyne
- Teledyne Energy Systems
- University of Michigan
- Michigan State University
- University of South Florida
- University of California at Davis
- Clemson University
- Princeton University
- Cornell University
- University of Southern California
- University of New Mexico

High Power TE Converter Technology Development Challenges

- **Technical risk reduction associated with high power conductively coupled thermoelectric (TE) power conversion systems**
  - **Highly compact, modular, conductively coupled TE converter technology compatible with large scale production**
  - **Performance compatible with wide range of heat source and heat rejection operating temperatures**
  - **High reliability throughout fabrication process and during operation (> 15 years)**

- **Key activities include:**
  - **Application of advanced thermal/mechanical/electrical modeling tools to develop converter design, fabrication and assembly that will result in maximum thermoelectric performance and lifetime**
  - **Large scale synthesis of high performance TE materials and fabrication of TE couples**
  - **Development of innovative large scale fabrication and assembly technology for TE couple arrays and converter assemblies**
  - **Extensive materials, components and sub-scale converter assembly testing**
  - **Lifetime performance prediction and validation through accelerated testing at the component and sub-scale converter assembly level**

Thermoelectric Converter Enhancements

Planned improvements to fabrication and performance of conductively coupled Thermoelectric SiGe couple stack developed for SP-100

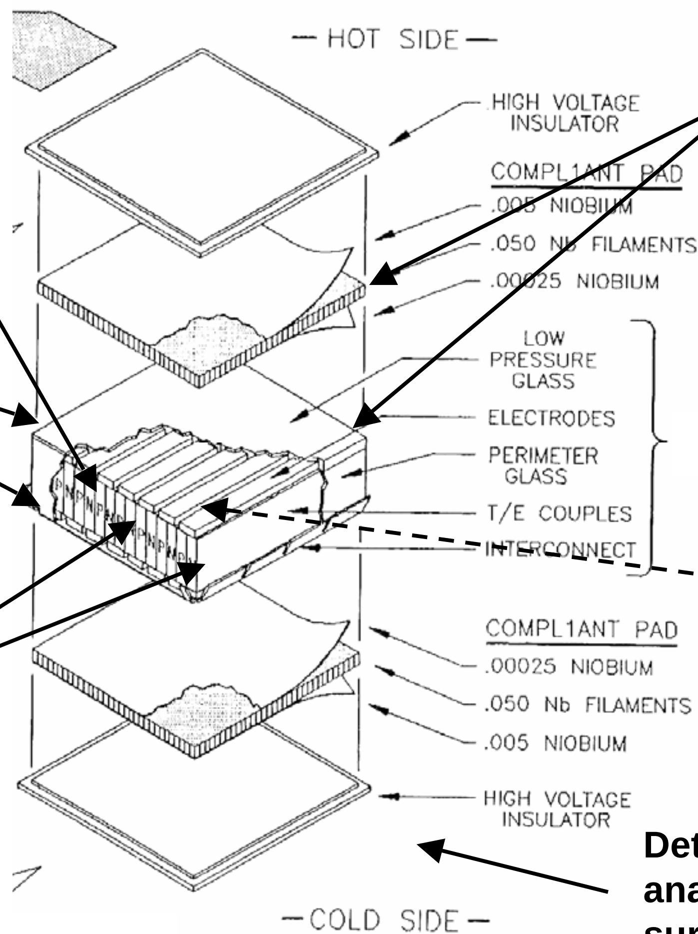
Improved TE Materials (increase conversion efficiency up to 10%)

Low contact resistance interconnects

(From 35-50 to less than 25 $\mu\Omega.cm^2$ at 1275K)

Refractory Aerogel for superior thermal insulation and ease of module/TCA assembly (no glass between couple legs or around legs)

Module arrangement facilitates interconnection (all handled from exterior of TCA)



SP-100 Multicouple (8-couple series)

Thick compliant pads and graphite layers reduced/eliminated to reduce waste ΔT from 30% to 5–10% (compliance achieved through structural engineering)

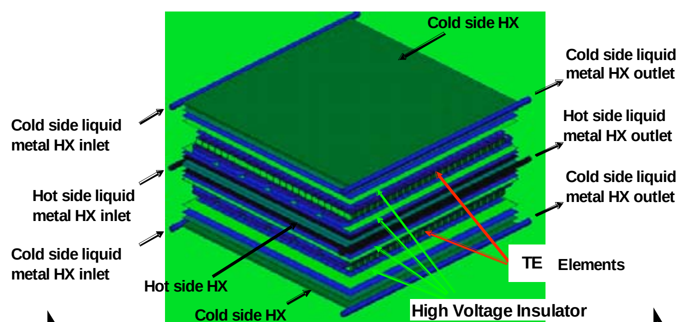
TE couples arranged in modules to facilitate fabrication, assembly and ensure lifetime

Detailed thermal/mechanical/fractural analysis for robust design that will survive fabrication, assembly and operation

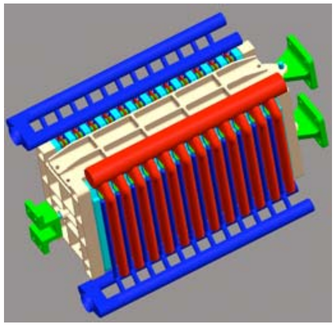
TE Power Converter Subsystem: Modular Technology Approach

- **TE is a modular technology that requires three discrete assemblies**
  - **Metallized TE legs**
  - **High voltage insulator/interconnect assembly**
  - **Heat exchanger assembly**
- **Bonding the three assemblies utilizes the same technology regardless of the assembly size**
  - **2x2 and 2x4 mini TCA modules**
  - **1/8 Sub-scale TCA modules**
  - **Thermoelectric Converter Assembly (TCA)**
  - **Power Converter Assembly (PCA)**
- **The fabrication technology is cost effective**
  - **Critical technology development is done at the smallest module level**
  - **TCA and PCA fabrication is directed at large assemblies issues**

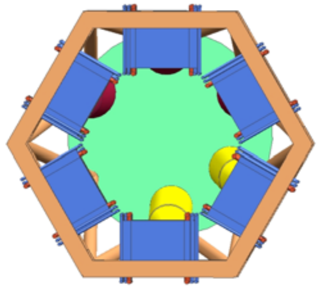
TE Module



TCA



PCA



PCS

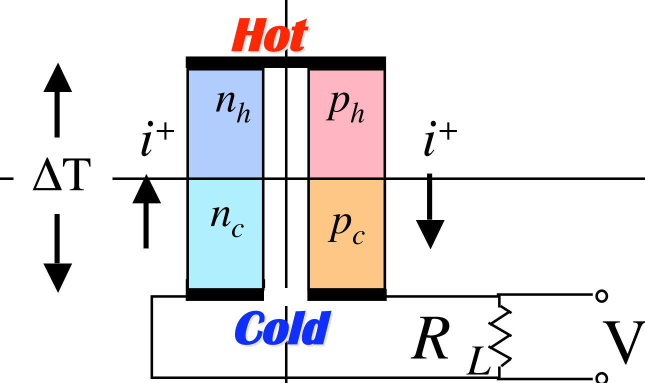
STMC High Temperature TE Materials Effort

High Temperature *n*-type

- La_2Te_3 published zT = 1.3
  - Needs to be reproduced
- Half Heusler
- Clathrates
- Skutterudites

High Temperature *p*-type

- Greatest development need
- $Cu_2Mo_6Se_8$ zT = 0.6
- Zintl
- Clathrates
- Skutterudites



- Materials effort only started in April/May 2004
  - Goal to achieve ZT >1.0 within 1275-700K
    - Minimum goal: 0.85
    - Compatible with Skutterudites
    - Thermal & mechanical stability
  - Down selection in March 2005

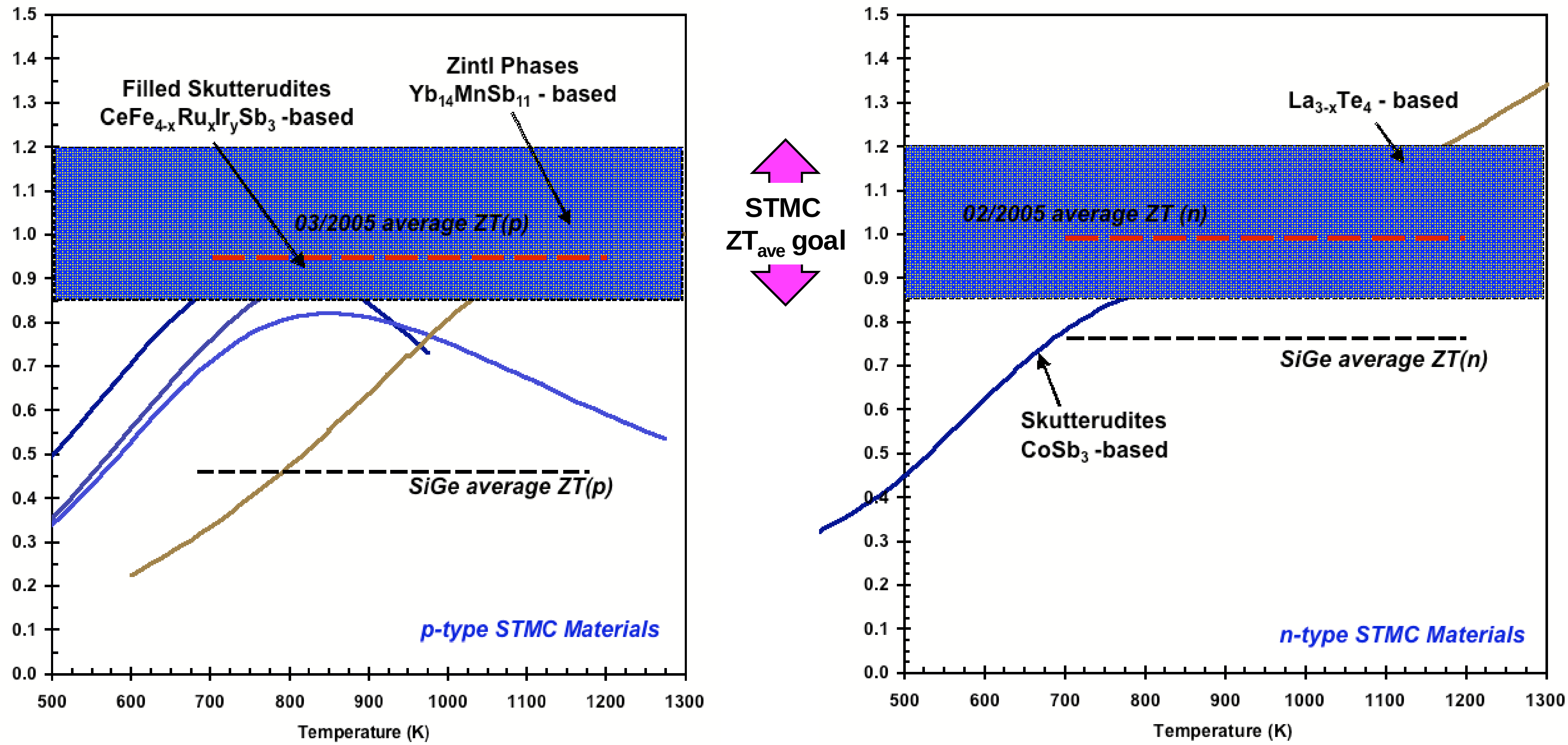
low Temperature *n*-type

- Skutterudite
- $CoSb_3$ today zT = 0.8
- ACo_4Sb_{12} goal zT = 1.1

low Temperature *p*-type

- Skutterudite
- $CeFe_4Sb_{12}$ today zT = 1.1
- $CeFe_4Sb_{12}$ goal zT = 1.4

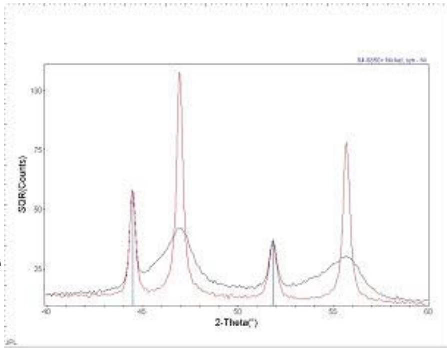
STMC Advanced TE Materials Status

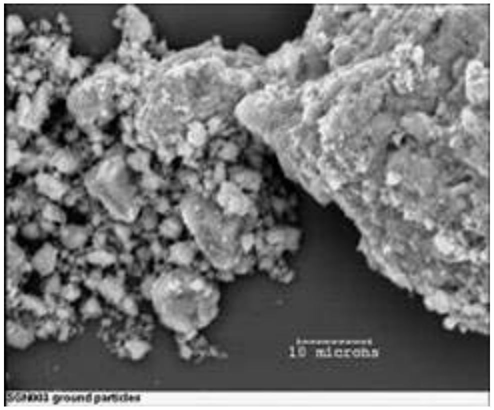


- **As of 05/2005, STMC combined p/n TE materials performance exceeds minimum goal of average ZT = 0.85 across 1200K-700K temperature differential**
- **Average ZT value of 0.95 about 50% better than that of SiGe alloys used in GPHS-RTG**
- **Materials downselect for high temperature STMC scheduled for late May 2005**

Large Scale Synthesis of TE Materials

- **Developed powder metallurgy techniques that can be scaled up to industrial quantities**
- **Selected use of mechanical alloying followed by hot pressing to synthesize $Si_{0.8}Ge_{0.2}$ alloys**
  - **Follows technology development initiated by Ames Laboratory in the early 1990s**
  - **Process is simpler, highly reproducible and less costly than one used in past SiGe programs**
- **High temperature pressure sintering for skutterudites**
  - **Segmented TE technology**
- **Developed scaled up synthesis of TE leg compacts for producing large numbers of legs**
  - **From 12.5 to 40 mm diameter compacts**
  - **HIP process also under evaluation**





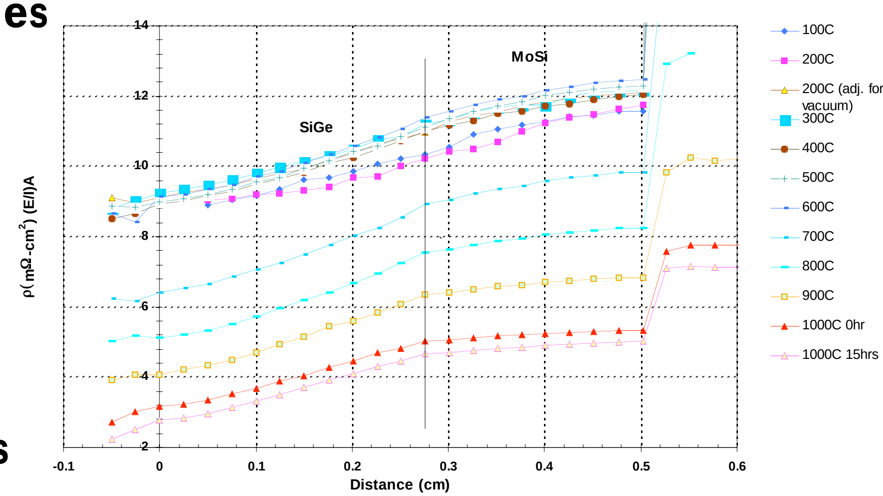
Low Contact Resistance TE/Interconnect Leg Bond

- **Contact resistance between TE materials and current electrodes was one of remaining issues in SP-100 program**
  - Low resistance, stable contact must be formed
  - All prior technology focused on developing contacts after synthesis of the TE materials
    - Best solution developed under SP-100 was complex SiGe/Mo/Ge/Mo/Graphite/W foil multilayer
    - Did not fully meet goal of < 25 μΩ.cm² required for multicouple technology
- **Achieved very low contact resistance values**
  - For both SiGe and skutterudites
    - Less than 5 μΩ.cm²
  - Bond achieved during direct leg fabrication
    - Low contact resistance bond, thermally stable
    - Fewer fabrication and assembly steps
    - Easy scale up
    - Electrical and mechanical life performance tests planned

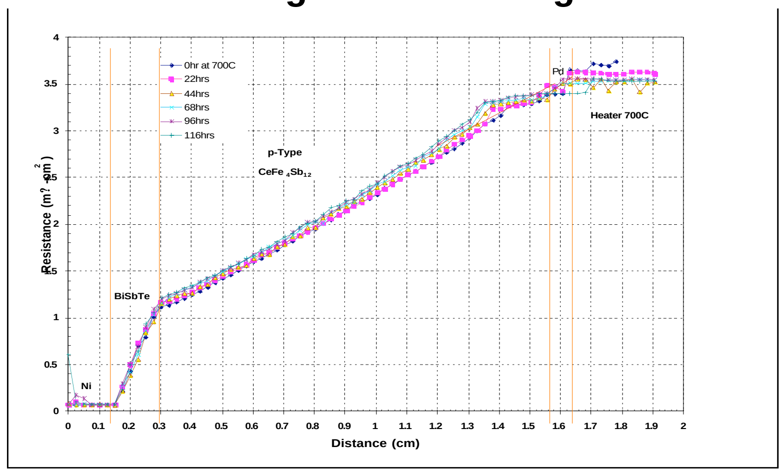
Mo-capped SiGe leg

Ti-capped Skutterudite leg

SiGe Leg



Segmented TE Leg



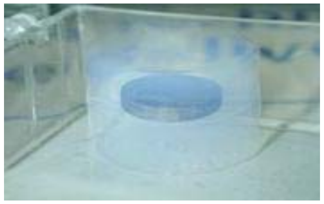
Contact Resistance Measurements

Sublimation and Thermal Insulation

- **Sublimation issue is TE material dependent**
  - **Testing to establish rates are under way**
  - **Aerogel is found effective and reduces rates to minimum (x100 lower rates)**
  - **Aerogel shows only minimal linear shrinkage below 1275K and has a much lower thermal conductivity than the glass used for SP-100**
  - **Metal coatings are also effective and have been extensively tested (sublimation eliminated)**
  - **Likely to use combination of both**

Uncoated TE material: beginning of life sublimation rate at operating temperature ($g/cm^2 \cdot hr$)	
TAGS at 775K	~ 1
Low Temperature n-Skutterudites (SKD) at 975K	~ 2.15×10^{-2}
Low Temperature p-Skutterudites (SKD) at 975K	~ 1.4×10^{-3}
Chevrels ($M_xMo_6Se_8$) at 1275K	~ 3.66×10^{-3}
$LaYbTe_x$ at 1275K	~ 2.11×10^{-4}
SiGe at 1275K	~ 4.8×10^{-5}

Aerogel: More than 100 times lower rates



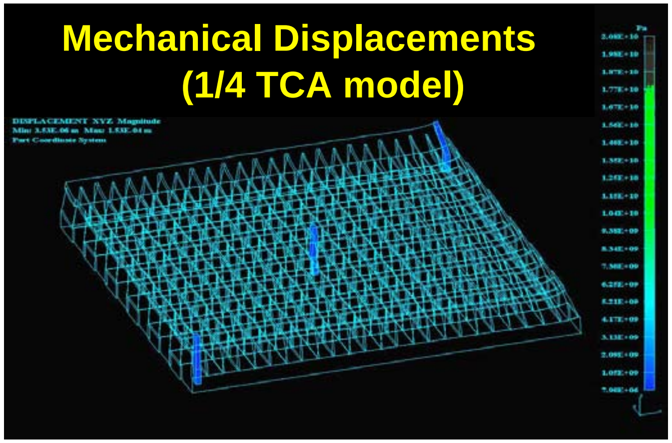
Metal coating: full sublimation suppression

STMC Mechanical Design & Engineering - Status

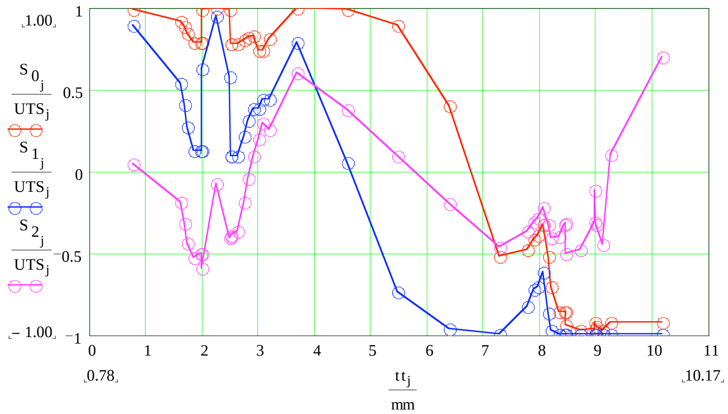
- **Key Structural Integrity Issues**
  - Coefficient of thermal expansion mismatches within TE device stack, and between stack and large heat exchangers
  - “Bowing” of thermoelectric legs due to large ΔT
  - Surviving fabrication and assembly steps – and operation

- **Reviewed preliminary design of STMC and TCA**
  - Key goal is to redistribute thermally induced stresses by selecting optimal materials combinations, element geometries
    - Optimized for steady-state operating conditions
    - Comparing models for SP-100 SiGe-based converter and STMC
    - Developed a rapid evaluation tool using an elastic model of the HT-TMC that allows to compare trends
  - Secondary objective is to minimize parasitic losses (ΔT across non-TE layers and fill factor thermal losses)
    - Initial calculations show only 10% losses (about 30% for SP-100)

- **Mechanical tests of TE samples**
  - 4-point bend data obtained on skutterudites and SiGe (comparable values at room temperature)
  - Testing and modeling of interface fracture toughness and development of fail-safe structures



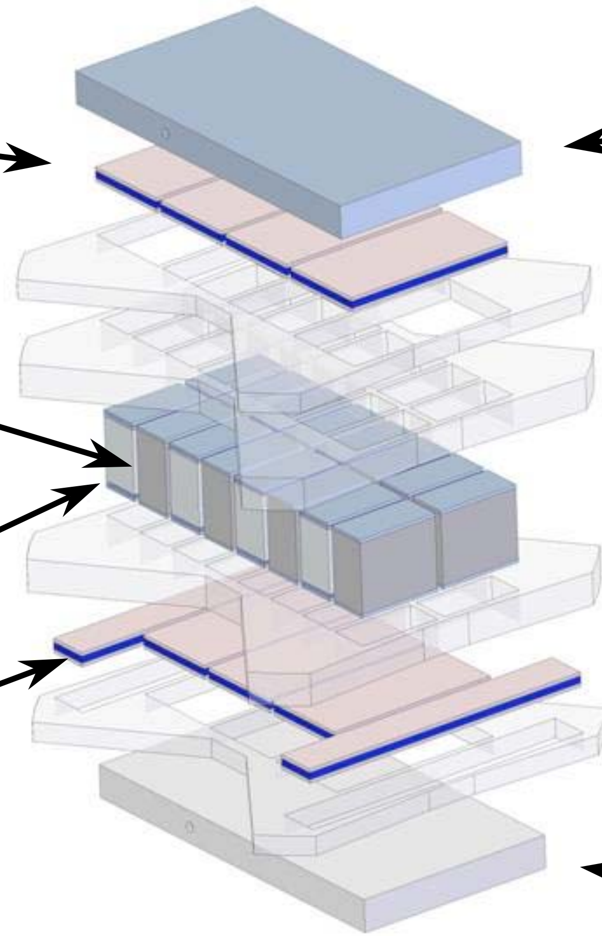
Elastic Stress Model of ½ STMC Stack
Red Line – Heat Exchanger Held Rigidly
Blue Line – Free to Expand but no Bending
Purple Line – Free to expand and bend



Fraction of Ultimate Strain VS Distance in mm

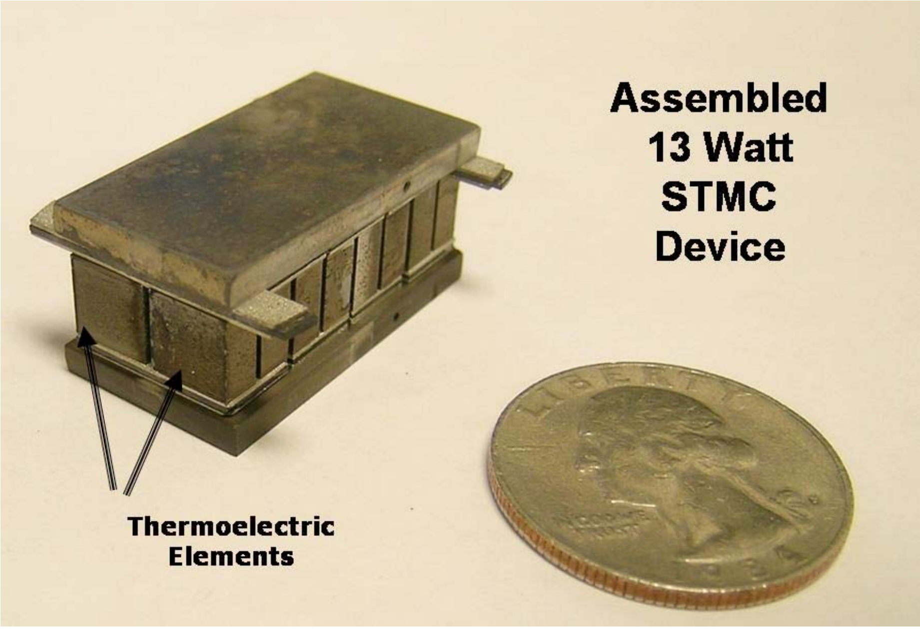
STMC Module

STMC Module fabrication: fewer and simpler fabrication steps, scalable to mass production

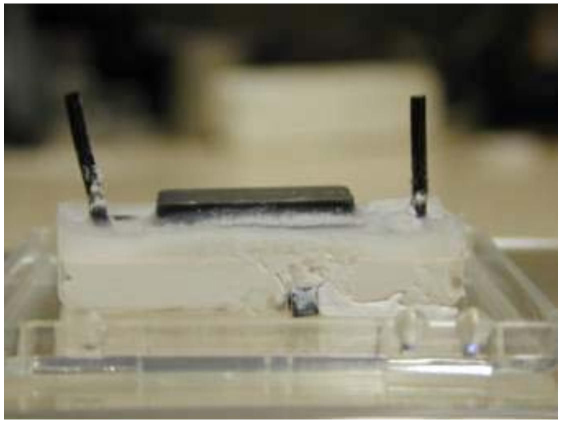


Segmented Thermoelectric Multicouple Converter (STMC)

LT-TMC Technology Demonstration Completed in May 2005



LT-TMC Teledyne Module #2
975K – 425K Operation, 13W



LT-TMC JPL Module #1
975K – 425K Operation, 5W